Chapter 9
Anchorage Systems

9-1. Scope

This chapter provides guidance for the design and evaluation of anchor systems used to prevent the sliding and/or overturning of laterally loaded structures founded on rock masses. This chapter supplements guidance provided in EM 1110-1-2907. The chapter is divided into two sections: Modes of Anchor-Rock Interaction and Methods of Analyses.

Section I
Modes of Anchor-Rock Interaction

9-2. General

Anchor systems may be divided into two general categories--tensioned and untensioned. The primary emphasis in the design, or selection of an anchorage system, should be placed on limiting probable modes of deformation that may lead to failure or unsatisfactory performance. The underlying premise of anchorage is that rock masses are generally quite strong if progressive failure along planes of low strength can be prevented. Both tensioned and untensioned anchors are suitable for the reduction of sliding failures in, or on, rock foundations. Tensioned anchor systems provide a means for prestressing all, or a portion, of a foundation, thus, minimizing undesirable deformations or differential settlements. Preconsolidation of rock foundations results in joint closure and what appears as strain hardening in some foundations.

9-3. Tensioned Anchor Systems

A typical prestressed anchorage system is shown in Figure 9-1. The use of grouted anchorages is practically universal, particularly with high capacity tendon systems. Upon tensioning, load is transferred from the tensioning element, through the grout, to the surrounding rock mass. A zone of compression is established (typically assumed as a cone) within the zone of influence. Tensioned anchor systems include rock bolts and rock anchors, or tendons. The following definitions are as given in EM 1110-1-2907.

a. Rock bolt. A tensioned reinforcement element consisting of a rod, a mechanical or grouted anchorage, and a plate and nut for tensioning or for retaining tension applied by direct pull or by torquing.

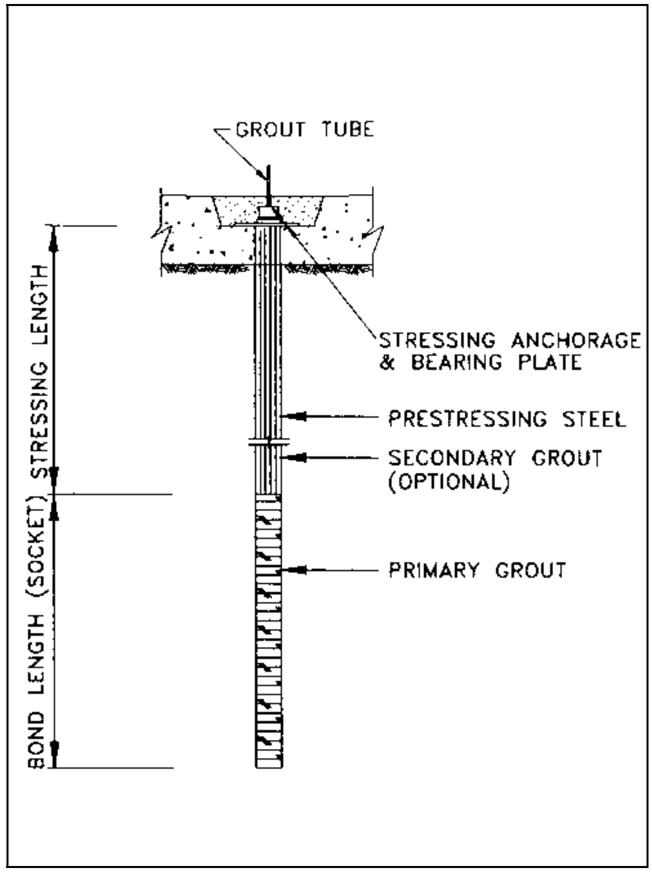

Figure 9-1. Typical components of a tensioned rock anchor (from EM 1110-1-2907)

b. Prestressed rock anchor or tendon. A tensioned reinforcing element, generally of higher capacity than a rock bolt, consisting of a high strength steel tendon (made up of one or more wires, strands, or bars) fitted with a stressing anchorage at one end and a means permitting force transfer to the grout and rock at the other end.

9-4. Untensioned Anchor Systems

Untensioned rock anchors are generally referred to as rock dowels and are defined in EM 1110-1-2907 as an untensioned reinforcement element consisting of a rod embedded in a mortar or grout filled hole. Dowels provide positive resistance to dilation within a rock mass and along potentially unstable contact surfaces. In addition to the development of tensile forces resisting dilation, passive resistance against sliding is developed within a rock mass when lateral strains occur. The interaction between the dowel and the rock mass is provided through the cohesion and friction developed along the grout column which bonds the rod and the rock. Untensioned anchor systems should not be used to stabilize gravity structures.

Section II
Methods of Analysis

9-5. General

Typically, analyses of systems used to anchor mass concrete structures consist of one of two methods: procedures based upon classical theory of elasticity or procedures based upon empirical rules or trial and error methods. The gap between the methods has been narrowed by research in recent years but has not significantly closed to allow purely theoretical analysis of anchor systems. The following discussions on methods of analyses are divided into tensioned and untensioned anchor systems.

9-6. Analyses for Tension Anchor Systems

The design and analysis of anchor systems include determination of anchor loads, spacing, depth, and bonding of the anchor. Safety factors are determined by consideration of the following failures; within the rock mass, between the rock and grout/anchor, between the grout and the tendon or rod, and yield of the tendon or top anchorage.

a. Anchor loads. Anchor loads for prestressed tensioned anchors are determined from evaluation of safety factor requirements of structures. Anchors may be designed for stability considerations other than sliding to include overturning and uplift. Other factors must also be considered. However, anchor forces required for sliding stability assurance typically control design. Procedures for determining anchor forces necessary for stability of concrete gravity structures are covered in EM 1110-2-2200.

b. Anchor depths. Anchor depths depend upon the type of rock mass into which they are installed and the anchor pattern (i.e., single anchor, single row of anchors, or multiple rows of anchors). The anchor depth is taken as the anchor length necessary to develop the anchor force required for stability. The entire anchor depth lies below the critical potential failure surface.

(1) Single anchors in competent rock. The depth of anchorage required for a single anchor in competent rock mass containing few joints may be computed by considering the shear strength of the rock mobilized around the surface area of a right circular cone with an apex angle of 90 degrees (see Figure 9-2a). If it is assumed that the in-situ stresses as well as any stresses imposed on the foundation rock by the structure is zero, then the shear strength can be conservatively estimated as equal to the rock mass cohesion. In such cases the anchor depth can be estimated from Equation 9-1.

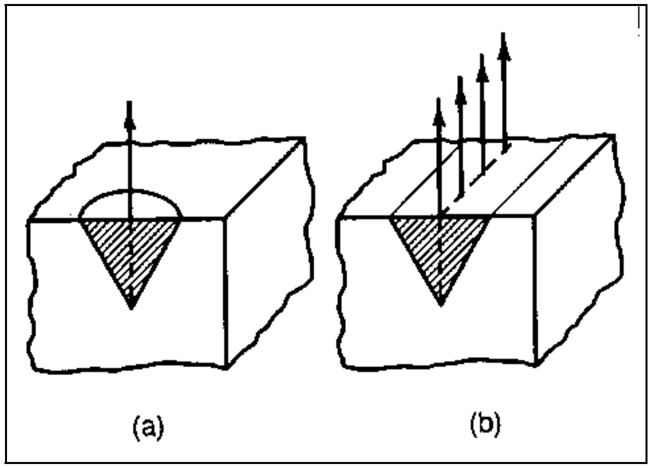

Figure 9-2. Geometry of rock mass assumed to be mobilized at failure (a) individual anchor in isotropic medium and (b) line of anchors in isotropic medium (after Littlejohn 1977)

$$D = [(FS)\ (F) / c\ \pi]^{1/2} \qquad (9\text{-}1)$$

where

D = the required depth of anchorage

FS = the appropriate factor of safety

c = the rock mass cohesion intercept

F = the anchor force required for stability

(2) Single row of anchors in competent rock. The depth of anchorage for a single row of anchors (see Figure 9-2b) installed in competent rock and spaced a distance s apart may be computed as follows:

$$D = \frac{(FS)\ (F)}{cs} \qquad (9\text{-}2)$$

where

F = the anchorage force on each anchor

All other parameters are as previously defined.

(3) Multiple rows of anchors in competent rock. For a multiple row of anchors with rows spaced a distance ℓ apart, typically, only the weight of the rock mass affected is used in calculations of resisting force. Under this assumption, the depth of anchorage required to resist a anchorage force *F* per anchor is computed as follows:

$$D = \frac{(FS)\ (F)}{\gamma\ \ell\ s} \tag{9-3}$$

where γ = the unit weight of the rock. All other parameters are as previously defined.

(4) Single anchor in fractured rock. In fractured rock, the strength of the rock mass subjected to a tensile force (the anchor force) cannot typically be relied upon to provide the necessary resistance. For this reason, only the weight of the affected one is considered. Based upon this assumption, the depth of anchorage is completed as follows:

$$D = \left(\frac{3\,(FS)\,(F)}{\gamma\ \pi}\right)^{1/3} \tag{9-4}$$

where γ = the unit weight of the rock. All other parameters are as previously defined.

(5) Single row of anchors in fractured rock. As in the case of a single anchor in fractured rock, typically only the weight of the affected wedge of rock is relied upon to provide the necessary resistance. Hence, for a single row of anchors in fractured rock spaced *S* distance apart, the anchorage depth is computed as follows:

$$D = \left(\frac{(FS)(F)}{\gamma\ S}\right)^{1/2} \tag{9-5}$$

All other parameters are as previously defined.

(6) Multiple rows of anchors in fractured rock. For multiple rows of anchors with rows spaced ℓ distance apart, again only the weight of the affected rock mass resists the anchor force. In this respect Equation 9-3 is valid.

c. Anchor bonding. The above equations, presented for analysis of anchor system, assume sufficient bond of the anchor to the rock such that failures occur within the rock mass. The use of grouted anchorages has become practically universal with most rock reinforcement systems. The design of grouted anchorages must, therefore, insure against failure between the anchor and the grout, as well as, between the grout and the rock. Experience and numerous pull-out tests have shown that the bond developed between the anchor and the grout is typically twice that developed between the grout and the rock. Therefore, primary emphasis in design and analysis is placed upon the grout/rock interface. For straight shafted, grouted anchors, the anchor force which can be developed depends upon the bond stress, described as follows:

$$F = \pi d L \tau \tag{9-6a}$$

$$\tau = 0.5\tau_{ult} \tag{9-6b}$$

where

d = the effective diameter of the borehole

L = length of the grouted portion of the anchor bond length (normally not less than 10 ft)

τ = the working bond strength

τ = the ultimate bond strength at failure

Values of ultimate bond strength are normally determined from shear strength data, or field pull-out tests. In the absence of such tests, the ultimate bond stress is often taken as 1/10 of the uniaxial compressive strength of the rock or grout (whichever is less) (Littlejohn 1977) up to a maximum value of 4.2 MPa (i.e., 600 psi).

9-7. Dowels

Structures should in principle be anchored, when required, to rock foundations with tensioned or prestressed anchorage. Since a displacement or partial shear failure is required to activate any resisting anchorage force, analysis of the contribution of dowels to stability is at best difficult. Dilation imparts a tensile force to dowels when displacements occur over asperities but the phenomenon is rarely quantified for analytical purposes.

9-8. Design Considerations

a. Material properties. The majorities of material properties required for the design of anchor systems are also typically required for the investigation of other aspects of the foundation design. The selection of appropriate material properties is discussed in Chapter 4 of this manual. Design anchor force derived from calculations not associated with sliding instability must consider the buoyant weight of rock where such rock is submerged below the surface water or ground water table. Tests not necessarily considered for typical foundation investigations but needed for anchor evaluations include rock anchor pull-out tests and chemical tests of the ground water. Rock anchor pull-out tests (Rock Testing Handbook, RTH 323) provide valuable data for determining anchorage depth and anchor bond strength. Hence, a prudent design dictates that pull-out tests be performed in the rock mass representative of the foundation conditions and anticipated anchor depths. Ground water chemical tests establish sulphate and chloride contents to be used as a guide in designing the anchor grout mix. In addition, the overall corrosion hazard for the anchor tendon steel should be established by chemical analysis. Such analyses are used to determine the amount and type of corrosion protection required for a particular foundation.

b. Factors of safety. The appropriate factor of safety to be used in the calculations of anchor force and anchorage depth must reflect the uncertainties and built-in conservatism associated with the calculation process. In this respect, anchor force calculations should be based on the factor of safety associated with sliding stability of gravity structures discussed in Chapter 7. Anchorage depth calculations based on the unit weight of the rock mass (Equations 9-3, 9-4, and 9-5) should use a minimum factor of safety of 1.5. All other anchorage depth calculations (i.e., Equations 9-1 and 9-2) should use a minimum factor of safety of 4.0 unless relaxed by CECW-EG for special circumstances.

c. Total anchor length. In addition to the anchor depth and anchor bonding considerations given by Equations 9-1 to 9-5 and Equation 9-6, respectively, the total anchor length (L_τ) is controlled by the location at which the rock mass is assumed to initiate failure should a general rock mass failure occur. Littlejohn and Bruce (1975) summarize the assumed location of failure initiation commonly used in practice. As indicated in Figure 9-3, three locations are commonly assumed: potential failure initiates at the base of the socket; potential failure initiates at the midpoint of the socket; or potential failure initiates at the top of the socket. The implication with respect to the total anchor length imposed by each failure location assumption is as shown in Figure 9-3. For the design of anchors in competent or fractured rock masses where the bond length is supported by pull-out tests, the potential for rock mass failure is assumed to initiate at the base of the anchor as shown in Figure 6-3a. For preliminary design where pull-out tests are not yet available or in highly fractured and very weak material, such as clay shale, the potential for failure is assumed to initiate at the midpoint of the socket as shown in Figure 6-3b. However, in the case of highly fractured and very weak material, pull-out tests must be performed to verify that the bond length is sufficient to develop the ultimate design load as specified in EM 1110-2-2000. Any relaxation in total anchor length requirements must be approved by CECW-EG.

d. Corrosion protection. The current industry standard for post-tensioned anchors in structures requires double corrosion protection for all permanent anchors.

e. Design process. The rock anchor design process is conveniently divided into two phases; the initial design phases and the final detailed phase. Additional details are provided in EM 1110-2-2200 and Post-Tensioning Institute (1986).

(1) Initial phase. The design process is initiated by an evaluation which finds that a given structure is potentially unstable without additional restraining forces. If the potential instability is due to potential for sliding, the magnitude of restraining forces is calculated according to procedures given in EM 1110-2-2200. Restraining forces necessary to control other modes of potential instability, such as overturning, uplift pressures, or excessive differential deformations are determined on a case-to-case basis. The magnitude of the required restraining force is evaluated with respect to the economics and practicality of using rock anchors to develop the necessary force.

(2) Final phase. The final detailed design phase is a trial and error process which balances economic and safety considerations with physical consideration of how to distribute the required restraining force to the structure and still be compatible with structure geometry and foundation conditions. While sequential design steps reflect the preference of the District Office, general design constraints usually dictate that the total restraining force be divided among a number of anchors. The number of anchors and hence the spacing between anchors and anchor rows, as well as the anchor orientation and installation details, are controlled by the geometry of the structure. Foundation conditions control the anchorage depth as well as the amount and type of corrosion protection. Anchor depths between adjacent anchors should be varied in order to minimize adverse stress concentrations.

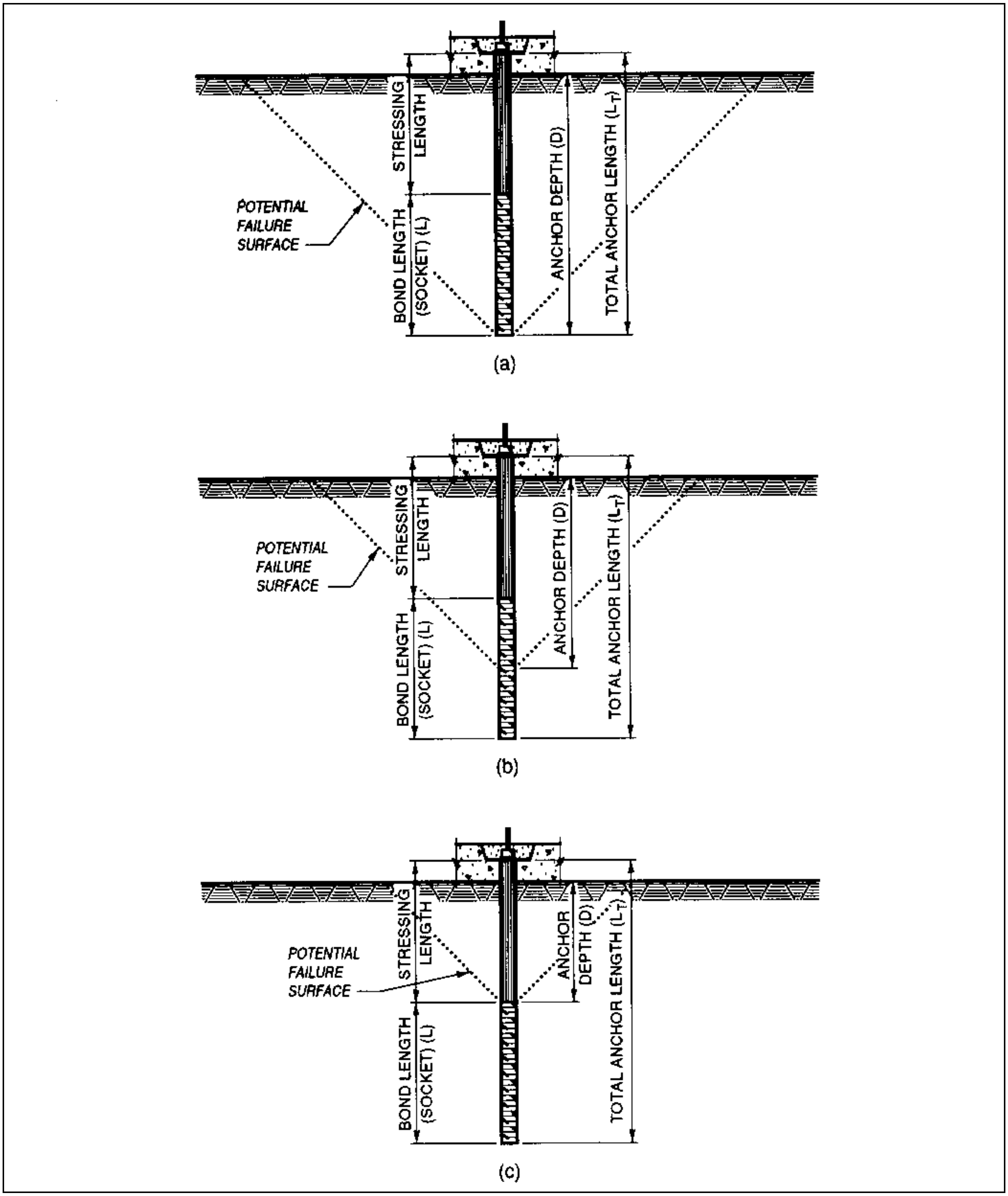

Figure 9-3. Potential failure surfaces commonly assumed for the design of anchor depths in rock masses: (a) potential failure initiates at the base of the socket; (b) potential failure initiates at the midpoint of the socket; (c) potential failure initiates at the top of the socket